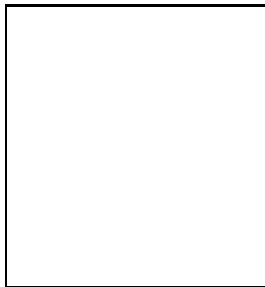


FINDING CP-VIOLATING HIGGSES

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In a general two-Higgs-doublet model with CP violation in the Higgs sector, the three neutral physical Higgs bosons have no definite CP properties. A new sum rule relating Yukawa and Higgs- Z couplings implies that a neutral Higgs boson cannot escape detection at an e^+e^- collider if it is kinematically accessible in Z +Higgs, $b\bar{b}$ +Higgs and $t\bar{t}$ +Higgs production, irrespective of the mixing angles and the masses of the other neutral Higgs bosons. The implications of the sum rules for Higgs discovery at the Tevatron and LHC are briefly mentioned.

1 Introduction

The origins of the electroweak symmetry breaking and the CP violation are still not understood. In the Standard Model (SM) the former is achieved spontaneously by the non-zero vacuum expectation value of the Higgs field, while the latter is parametrized by the complex Yukawa Higgs-fermion couplings. Although such a minimal model of the electroweak interactions describes exceedingly well a wealth of experimental data, the SM cannot be considered as a fundamental theory since neither the structure of the model, nor its parameters are predicted. They are merely built in.

The models of mass generation by elementary scalars predict one (like in the SM) or more physical Higgs bosons. Already the simplest extension of the SM with two scalar Higgs doublets (2HDM) predicts the existence of 5 physical Higgs bosons: three electrically neutral and a charged pair. The CP-conserving (CPC) version of the 2HDM has received a considerable attention, especially in the context of the minimal supersymmetric model (MSSM). It predicts two neutral Higgs bosons (h^0 and H^0) to be CP-even and one CP-odd neutral state (A^0). However, such a distinction may get lost beyond the Born approximation if the soft SUSY breaking parameters have a nonzero CP-violating phases¹. As a result, all three neutral Higgs states may mix and the mass eigenstates h_1 , h_2 and h_3 will have no definite CP properties.

In a general (non-supersymmetric) 2HDM the Higgs sector itself may also generate CP violation (CPV). The possibility that CP violation, spontaneous and/or explicit, derives largely (or entirely) from the Higgs sector is particularly appealing². In the CPV 2HDM the neutral Higgs bosons mix already at the tree level. From the phenomenological point of view, a critical question then arises whether the additional freedom in Higgs boson couplings is sufficient to jeopardize our ability to find light neutral Higgs bosons. We will see that the unitarity of the model implies a number of interesting sum rules for the Higgs-gauge boson^{3,4} and Higgs-fermion⁵ couplings that guarantee the discovery in e^+e^- collisions of any neutral Higgs boson that is sufficiently light to be kinematically accessible in (a) the Higgs-strahlung, (b) the Higgs-pair production or (c) the $t\bar{t}$ +Higgs processes.

2 Sum rules for the Higgs boson couplings

We consider the CPV 2HDM of electroweak interactions with two SU(2) Higgs doublets $\Phi_1 = (\phi_1^+, \phi_1^0)$ and $\Phi_2 = (\phi_2^+, \phi_2^0)$ defined⁵ by the potential

$$V(\Phi_1, \Phi_2) = -\mu_1^2 \Phi_1^\dagger \Phi_1 - \mu_2^2 \Phi_2^\dagger \Phi_2 + \lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 |\Phi_1^\dagger \Phi_2|^2 + [\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \text{h.c.}] - [\mu_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.}] \quad (1)$$

and the Yukawa couplings

$$\mathcal{L}_Y = -(\bar{u}_i, \bar{d}_i)_L \Gamma_u^{ij} \tilde{\Phi}_2 u_{jR} - (\bar{u}_i, \bar{d}_i)_L \Gamma_d^{ij} \Phi_1 d_{jR} - (\bar{\nu}_i, \bar{e}_i)_L \Gamma_e^{ij} \Phi_1 e_{jR} + \text{h.c.}, \quad (2)$$

where i, j are generation indices and $\tilde{\Phi}_2$ is defined as $i\sigma_2 \Phi_2^*$.

If $\text{Im}(\mu_{12}^{*4} \lambda_5) \neq 0$, the CP is violated explicitly. When $\text{Im}(\mu_{12}^{*4} \lambda_5) = 0$, but $|\mu_{12}^2/2\lambda_5 v_1 v_2| < 1$, CP is spontaneously violated since the minimum of the potential occurs for $\langle \Phi_1 \rangle = v_1/\sqrt{2}$ (without loss of generality, v_1 is positive) and $\langle \Phi_2 \rangle = v_2 e^{i\theta}/\sqrt{2}$, where $\cos \theta = \mu_{12}^2/2\lambda_5 v_1 v_2$. In this normalization $v \equiv \sqrt{v_1^2 + v_2^2} = 2m_W/g = 246 \text{ GeV}$.

After SU(2)×U(1) gauge symmetry breaking, the state $\sqrt{2}(c_\beta \text{Im}\phi_1^0 + s_\beta \text{Im}\phi_2^0)$ becomes a would-be Goldstone boson which is absorbed in giving mass to the Z gauge boson. (Here, we use the notation $s_\beta \equiv \sin \beta$, $c_\beta \equiv \cos \beta$, where $\tan \beta = v_2/v_1$.) The remaining three neutral degrees of freedom ($\varphi_1, \varphi_2, \varphi_3$) $\equiv \sqrt{2}(\text{Re}\phi_1^0, \text{Re}\phi_2^0, s_\beta \text{Im}\phi_1^0 - c_\beta \text{Im}\phi_2^0)$ are not mass eigenstates. The physical neutral Higgs bosons h_i ($i = 1, 2, 3$) are obtained by an orthogonal transformation, $h = R\varphi$, where the rotation matrix is given in terms of three Euler angles ($\alpha_1, \alpha_2, \alpha_3$) by

$$R = \begin{pmatrix} c_1 & -s_1 c_2 & s_1 s_2 \\ s_1 c_3 & c_1 c_2 c_3 - s_2 s_3 & -c_1 s_2 c_3 - c_2 s_3 \\ s_1 s_3 & c_1 c_2 s_3 + s_2 c_3 & -c_1 s_2 s_3 + c_2 c_3 \end{pmatrix}, \quad (3)$$

where $s_i \equiv \sin \alpha_i$ and $c_i \equiv \cos \alpha_i$. Without loss of generality, we assume $m_{h_1} \leq m_{h_2} \leq m_{h_3}$. The Yukawa interactions of the h_i mass-eigenstates are not invariant under CP

$$\mathcal{L} = h_i \bar{f} (S_i^f + i P_i^f \gamma_5) f, \quad (4)$$

where the scalar (S_i^f) and pseudoscalar (P_i^f) couplings are functions of the mixing angles. For up-type ($f = u$) and down-type ($f = d$) quarks we have

$$S_i^u = -\frac{m_u}{vs_\beta} R_{i2}, \quad P_i^u = -\frac{m_u}{vs_\beta} c_\beta R_{i3}, \quad \text{and} \quad S_i^d = -\frac{m_d}{vc_\beta} R_{i1}, \quad P_i^d = -\frac{m_d}{vc_\beta} s_\beta R_{i3}, \quad (5)$$

and similarly for charged leptons.

The absence of any $e^+e^- \rightarrow Zh_{\text{SM}}$ signal in LEP data translates into a lower limit on $m_{h_{\text{SM}}}$. The latest analysis of four LEP experiments at \sqrt{s} up to 189 GeV implies $m_{h_{\text{SM}}}$ greater than about 90 GeV⁶. The negative results of Higgs boson searches at LEP can be formulated as restrictions on the parameter space of the 2HDM and more general Higgs sector models. As has been shown in Refs.^{3,4}, the sum rules for the Higgs- Z boson couplings derived in the CP-conserving 2HDM can be generalized to the CP-violating case to yield a sum rule

$$C_i^2 + C_j^2 + C_{ij}^2 = 1, \quad (6)$$

where $i \neq j$ are any two of the three possible indices, and C_i and C_{ij} denote the reduced ZZh_i and Zh_ih_j couplings

$$C_i \equiv \left(\frac{gm_Z}{c_W}\right)^{-1} g_{ZZh_i} = s_\beta R_{i2} + c_\beta R_{i1}, \quad (7)$$

$$C_{ij} \equiv \left(\frac{g}{2c_W}\right)^{-1} g_{Zh_ih_j} = (s_\beta R_{i1} - c_\beta R_{i2}) R_{j3} - (s_\beta R_{ij} - c_\beta R_{j2}) R_{i3}. \quad (8)$$

The power of Eq. (6) with $i, j = 1, 2$ for LEP physics derives from two facts: it involves only two of the neutral Higgs bosons; and the experimental upper limit on any one C_i^2 derived from $e^+e^- \rightarrow Zh_i$ data is very strong: $C_i^2 \lesssim 0.1$ for $m_{h_i} \lesssim 70$ GeV. Thus, if h_1 and h_2 are both below about 70 GeV in mass, then Eq. (6) requires that $C_{12}^2 \sim 1$, whereas for such masses the limits on $e^+e^- \rightarrow h_1h_2$ from LEP2 data require $C_{12}^2 \ll 1$. As a result, there cannot be two light Higgs bosons even in the general CP-violating case; the excluded region in the (m_{h_1}, m_{h_2}) plane that results from a recent analysis by the DELPHI Collaboration is quite significant⁷.

If even one of the three processes, Zh_1 , Zh_2 (Higgs-strahlung) and h_1h_2 (pair production), is beyond the collider's kinematical reach, the sum rule in Eq. (6) is not sufficient to guarantee h_1 or h_2 discovery even if there is a light h_i . For example, with $C_{12} \sim 1$ and $C_{1,2} \sim 0$ satisfying eq. (6), the h_1h_2 production could be kinematically closed while Zh_1 and Zh_2 production would be suppressed by C_1 and C_2 . However, in this case we can exploit another sum rule derived in⁵ which constrain the Yukawa and ZZ couplings of any one Higgs boson, namely (for obvious reasons we consider the third generation fermions)

$$\begin{aligned} (\hat{S}_i^t)^2 + (\hat{P}_i^t)^2 &= \left(\frac{\cos \beta}{\sin \beta}\right)^2 \left[1 + \frac{C_i}{\cos^2 \beta} (2\hat{S}_i^b \cos^2 \beta + C_i)\right]; \\ (\hat{S}_i^b)^2 + (\hat{P}_i^b)^2 &= \left(\frac{\sin \beta}{\cos \beta}\right)^2 \left[1 + \frac{C_i}{\sin^2 \beta} (2\hat{S}_i^t \sin^2 \beta + C_i)\right]. \end{aligned} \quad (9)$$

where $\hat{S}_i^f \equiv S_i^f v/m_f$, $\hat{P}_i^f \equiv P_i^f v/m_f$. Combining the two sum rules we get

$$\sin^2 \beta [(\hat{S}_i^t)^2 + (\hat{P}_i^t)^2] + \cos^2 \beta [(\hat{S}_i^b)^2 + (\hat{P}_i^b)^2] = 1 \quad (10)$$

independently of C_i . Eq. (10) implies that the Yukawa couplings to top and bottom quarks cannot be simultaneously suppressed, *i.e.* if $C_i \sim 0$ at least one h_i Yukawa coupling must be large. The complete Higgs hunting strategy at e^+e^- colliders, and at hadron colliders as well, should therefore include not only the Higgs-strahlung and Higgs-pair production but also the Yukawa processes^a with Higgs radiation off top and bottom quarks in the final state.

^aThe importance of the Yukawa processes in the context of a CP conserving 2HDM for large $\tan \beta$ has been stressed in the past many times^{8,9}.

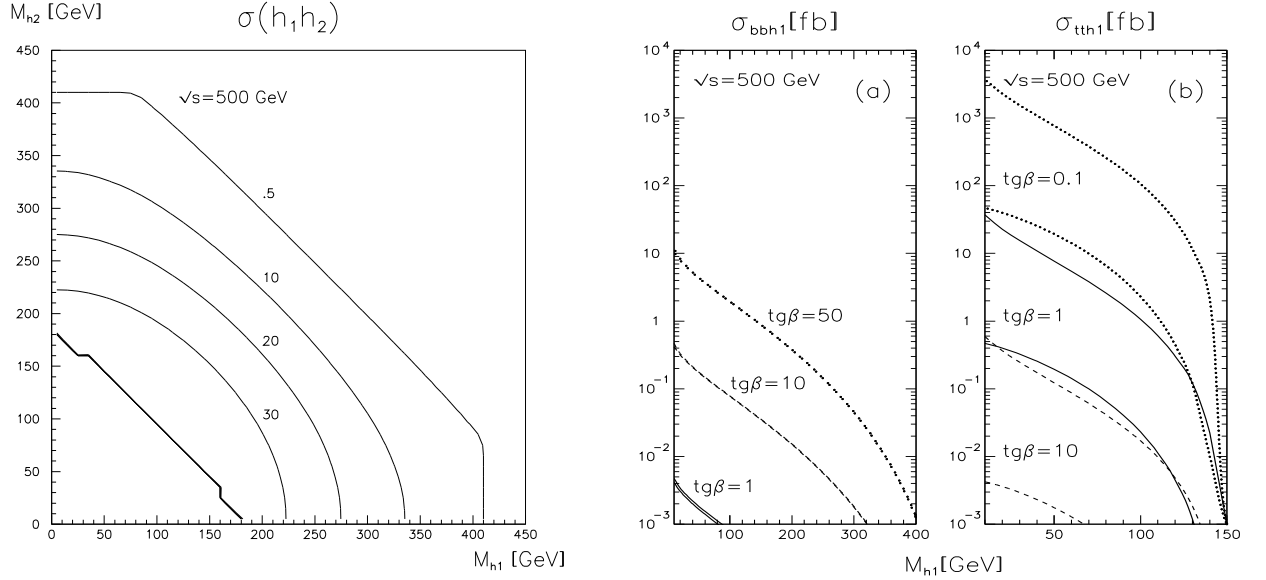


Figure 1: *Left panel:* Contour lines for $\min[\sigma(e^+e^- \rightarrow h_1 h_2)]$ in units of fb's. The contour lines are plotted for $\tan\beta = 0.5$; the plots are virtually unchanged for larger values of $\tan\beta$. The contour lines overlap in the inner corner as a result of excluding mass choices inconsistent with experimental constraints from LEP2 data. *Right panel:* The minimal and maximal values of the cross sections for $e^+e^- \rightarrow b\bar{b}h_1$ (a) and $e^+e^- \rightarrow t\bar{t}h_1$ (b), the same type of line (dots for $\tan\beta = 0.1$ and $t\bar{t}h_1$, solid for $\tan\beta = 1$, dashes for $\tan\beta = 10$, dots for $\tan\beta = 50$ and $b\bar{b}h_1$) is used for the minimal and maximal values of the cross sections. In the case of $b\bar{b}h_1$, the minimal and maximal values of the cross sections are almost the same. Masses of the remaining Higgs bosons are assumed to be 1000 GeV.

3 Higgs boson production in e^+e^- colliders

In order to treat the three h_1 production mechanisms: (a) $e^+e^- \rightarrow Zh_1$, (b) $e^+e^- \rightarrow h_1 h_2$, and (c) the Yukawa processes $e^+e^- \rightarrow f\bar{f}h_1$, on the same footing, we consider the $f\bar{f}h_1$ final state at future e^+e^- colliders. The processes (a) and (b) contribute to this final state when $Z \rightarrow f\bar{f}$ and $h_2 \rightarrow f\bar{f}$, respectively. Since all fermion and Higgs boson masses in the final state must be kept nonzero, the formulae for the cross section are quite involved. They can be found in⁵.

If the coupling of the h_1 to the Z boson is not dynamically suppressed, *i.e.* C_1 is substantial, then the Higgs-strahlung process, $e^+e^- \rightarrow Zh_1$, will be sufficient to find it. In the opposite case, which is a main focus of my talk, one has to consider the other processes (b) and/or (c), for which the sum rules (6) and (9) will imply that the neutral Higgs boson(s), if kinematically accessible, will be produced at a comfortably high rate at a high luminosity future linear e^+e^- collider¹⁰. For definiteness we will take an e^+e^- collider with $\sqrt{s} = 500$ GeV and integrated luminosity $L = 500 \text{ fb}^{-1}$ and assume that C_i are suppressed so that fewer than 50 Zh_i events are expected. We will consider two situations:

- (i) two light Higgs bosons: *i.e.* $m_{h_1} + m_{h_2}, m_{h_1} + m_Z, m_{h_2} + m_Z < \sqrt{s}$. If $C_1, C_2 \ll 1$, then from Eq. (6) it follows that Higgs pair production is at full strength, $C_{12} \sim 1$. In the left panel of Fig.1 contour lines are shown for the minimum value of the pair production cross section, $\sigma(e^+e^- \rightarrow h_1 h_2)$ as a function of Higgs boson masses. The minimum of $\sigma(h_1 h_2)$ is found by scanning over the mixing angles α_i consistent with present experimental constraints on C_i (which roughly exclude $m_{h_1} + m_{h_2} \lesssim 180$ GeV) and the above assumption of less than 50 Zh_i events. With $L = 500 \text{ fb}^{-1}$ a large number of events (large enough to allow for selection cuts and experimental efficiencies) is predicted for a broad range of Higgs boson masses. If 50 events before cuts and efficiencies prove adequate (*i.e.* $\sigma > 0.1 \text{ fb}$), one can probe reasonably close to the kinematic boundary defined by requiring that $m_{h_1} + m_Z, m_{h_2} + m_Z$ and $m_{h_1} + m_{h_2}$ all be less than \sqrt{s} .
- (ii) one light Higgs boson: *i.e.* $m_{h_1} + m_Z < \sqrt{s}, m_{h_1} + m_{h_2}, m_{h_2} + m_Z > \sqrt{s}$. If C_1 is small the sum rules (9) imply that Yukawa couplings may still allow detection of the h_1 . This is demonstrated

in the right panel of Fig. 1, where the minimum and maximum values of $\sigma(e^+e^- \rightarrow f\bar{f}h_1)$ for $f = t$ (a) and $f = b$ (b) are drawn as functions of the Higgs boson mass. It is seen that if m_{h_1} is not large there will be sufficient events in either the $b\bar{b}h_1$ or the $t\bar{t}h_1$ channel (and perhaps both) to allow h_1 discovery. The smallest reach in m_{h_1} arises if $1 \lesssim \tan\beta \lesssim 10$ and the α_i 's are such that the $t\bar{t}h_1$ cross section is minimal. Taking again 50 events as the observability criteria, at $\tan\beta = 1$ we have $\sigma(b\bar{b}h_1) \ll 0.1$ fb for all m_{h_1} while $\sigma_{\min}(t\bar{t}h_1)$ falls below 0.1 fb for $m_{h_1} > 70$ GeV. At $\tan\beta = 10$, $\sigma_{\min}(t\bar{t}h_1) \ll 0.1$ fb and $\sigma_{\min}(b\bar{b}h_1) \simeq \sigma_{\max}(b\bar{b}h_1)$ falls below 0.1 fb for $m_{h_1} > 80$ GeV. A $\sqrt{s} = 1$ TeV machine would considerably extend this mass reach.

The generalization to models with additional Higgs singlets modifies the sum rules. Each singlet field introduces two more physical neutral Higgs bosons which do not couple to Z or to fermions. As a result, in the sum rule (10), the factor 1 in the RHS is replaced by the “two-duoblet content” of the h_i . At least $1 + 2N_{\text{singlet}}$ of the neutral Higgs bosons must be light in order to guarantee⁵ that at least one of them will be observed in $t\bar{t}h_i$ or $b\bar{b}h_i$ associated production.

4 Conclusions

The new sum rule, Eq. (9), relating the Yukawa and Higgs- Z couplings of a general CP-violating two-Higgs-doublet model implies that any one of the three neutral Higgs bosons that is light enough to be produced in $e^+e^- \rightarrow t\bar{t}h$ (implying that $e^+e^- \rightarrow Zh$ and $e^+e^- \rightarrow b\bar{b}h$ are also kinematically allowed) will be found at an e^+e^- linear collider of sufficient luminosity. These same guarantees for the CPV 2HDM model do not apply to the Tevatron and LHC hadron colliders. In the case of the Tevatron, the small rate for $t\bar{t}$ +Higgs production is a clear problem¹¹. In the case of the LHC, a detailed study would be appropriate. However, existing studies in the context of supersymmetric models can be used to point to parameter regions that are problematical because of large backgrounds and/or signal dilution due to sharing of available coupling strength. Still, it is clear that the sum rules are sufficiently powerful to imply that such parameter regions are of fairly limited extent.

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